SUMMARY SESSION B: MORE OBSERVATIONS AT EXISTING ACCELERATORS AND CONCERNS FOR FUTURE MACHINES

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Abstract

Beginning with the International Workshop on Multi-bunch Instabilities in Tsukuba (KEK, 1997) [1], and continuing with special Electron Cloud workshops in Santa Fe (LANL/ANL, 2000) [2], Tsukuba (KEK, 2001) [3], Geneva (CERN, 2002) [4] and the present workshop, it is remarkable that new observations of electron cloud effects continue to be reported, spreading from proton rings to positron and electron rings to heavy-ion linacs and rings. This paper summarizes a rich collection of recent observations, as well as issues for future machines, presented in Session B. An attempt is also made to summarize conclusions and questions raised by the presenters.

OUTLINE

The papers in this session can be grouped as follows:

High-energy short-pulse proton rings

J. M. Jiménez, "Electron cloud and vacuum effects in the SPS"

T. Kroyer, "Unexpected results on microwave waveguide mode transmission measurements in the SPS beam-pipe"

Medium/high-energy long-pulse proton rings

R. Macek, "Experimental studies of electron cloud effects at the Los Alamos PSR: A status report"

T. Toyama, "EC effects in the J-PARC rings and related topics"

Heavy-ion rings and linacs

W. Fischer, "Electron clouds and vacuum pressure rise in RHIC"

A. Drees, "Correlation of pressure rise and experimental backgrounds at RHIC in Run04"

A. Molvik, "Experimental studies of electron and gas sources in a heavy-ion beam"

High-energy positron/electron rings

A. Novokhatski, "Experimental and simulation studies of electron cloud and multipacting in the presence of small solenoidal fields"

A. Temnykh, Comments on preliminary results at CESR

Short pulse vs. long pulse is a somewhat arbitrary categorization for proton rings based on the dynamics between the electron cloud and proton bunches, including the mechanism for amplification of the cloud. In a long pulse, essentially all the electrons in the chamber are trapped in the bunch potential during the bunch passage. The electron cloud can be amplified through trailing-edge multipactor, a term coined by R. Macek and his colleagues. In a short pulse, the electrons are not all trapped, and an impulse-kick approximation is assumed to be valid for the interaction between the beam bunch and the electrons (not strictly true because electrons near even a very short bunch can oscillate several times in the bunch potential [5]). The cloud can be amplified given certain values of the bunch spacing and bunch intensity and sufficiently large secondary electron yield coefficient, characterized by its peak value δ_{max}. In reality, the distinction short or long pulse is only a matter of degree, but it is retained for convenience and for historical reasons.

HIGH-ENERGY SHORT-PULSE PROTON RINGS

SPS

Two new, specialized electron cloud (EC) diagnostics were developed and installed in the Super Proton Synchrotron (SPS) at CERN. The cold strip detector allows measurements to be made in a superconducting dipole magnet liner at 30 K. The variable aperture strip detector allows measurements of the EC corresponding to different chamber heights. These diagnostics were designed to compare surface conditioning through beam scrubbing in warm vs. cold chambers and in dipole field (DF) vs. field-free (FF) regions. Results were also compared for different bunch spacing. These data contribute to predictions of beam conditioning efficiency during startup of the Large Hadron Collider (LHC).

J. M. Jiménez reported several new results with LHC beams in SPS, i.e., 25-ns bunch spacing and 1.1×10^{11} protons per bunch. Surface conditioning consists of two parts: vacuum scrubbing (through desorption of gas molecules) and lowering of the secondary electron emission (beam conditioning). Vacuum pressure was reduced after running with beam at room temperature (RT) in both DF and FF. Beam conditioning was observed at both RT and at cold temperatures (30 K), although a faster rate of conditioning was noted in FF at RT. The goal of reducing δ_{max} to 1.5 can be reached after 4 days, in good agreement with analytical calculations.

However, beam conditioning is limited at first by the available cryogenic cooling power: increased electron cloud activity increases the heat deposition on the walls. Reduced but non-zero conditioning with a 75-ns spacing appears possible (cloud activity reduced by an order of magnitude). The larger bunch spacing is more favorable than lowering the bunch intensity. In the latter case, the EC energy spectrum changes and the spatial distribution of the dense EC stripes in the DF moves, possibly overlapping with the slots in the cold liner and allowing elec-

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tron bombardment of the cold bore. One complication is that the stripe spatial distribution evolves with beam conditioning as well. In addition, the stripe positions also change with bunch spacing. With the larger bunch spacing or lower bunch intensity, reaching the goal for δ_{max} may require 13-19 days.

Other results were reported. The energy ramp in the SPS has a detrimental effect on the EC DF stripes; a central stripe (i.e., in the beam) grows rapidly on ramping the energy. Also, EC survival over 550-ns gaps between 77-bunch trains was measured: the EC built up after the 20th bunch in the first train, but it grew almost immediately after the gap in the 2nd the 3rd train. There are remaining questions about the effect of the bunch length on EC and vacuum effects (the LHC bunch length is shorter than in the SPS). The future experimental program includes installing electron detectors in the quadrupoles and higher spatial-resolution (1-mm) detectors in the dipoles (lithographed kapton foil).

Microwave TE-Mode Transmission Diagnostic

Preliminary results were reported by T. Kroyer of an idea first proposed by S. Heifets to measure the averaged EC density in the vacuum chamber (in contrast to the wall flux measured by standard devices such as the ANL Retarding Field Analyzer (RFA)). The EC-induced modulation of a TE wave propagating over a 30-m section of the SPS with dipoles was measured for many different machine conditions and microwave frequencies. Surprisingly, strong amplitude modulation (AM) was observed in addition to the expected phase modulation (PM); this AM is not consistent with present EC models. The signal attenuation was greater than what was expected for the EC (the TE wave should not interact with the beam). The attenuation showed memory effects (lifetime and/or build-up time) of the order of a few μs after a bunch passage. An explanation is not yet clear, although there is speculation that charged dust particles may be involved. Additional observations include an electron cyclotron resonance of 28 GHz/T with very asymmetric spectra at injection, erratic tails in the time domain, no changes with variations in vacuum pressure, and no threshold behavior analogous to cloud saturation.

MEDIUM/HIGH-ENERGY LONG-PULSE PROTON RINGS

PSR (800-MeV SR)

R. Macek presented an extensive summary of the many EC studies carried out over the years at the LANL Proton Storage Ring (PSR); details can also be found elsewhere [6]. It was at the PSR that the Electron Sweeper diagnostic was introduced: a curved electrode installed opposite an RFA. The electrons over a fraction (~30%) of the chamber cross-sectional area are swept into the RFA when the electrode is pulsed; the energy distribution is lost, but low-energy electrons that do not collide with the walls can thereby be measured. A second innovation was adding an amplifier to the RFA collector to allow time-resolved measurements. First-ever data on trailing-edge multipacting were acquired with fast RFAs ("prompt" electrons), and electron survival in the long, ~100-ns gap was characterized with the sweeper ("swept" electrons). From these data, a neutralization lower limit of ~1% and a low-energy secondary electron yield coefficient δ_0 = 0.5 were obtained. The decay time of electrons in the gap is ~170 ns; in contrast to the prompt electrons, this quantity was found to be quite insensitive to beam parameters and surface conditions. Reasonable comparisons with the data have been obtained with EC modeling, but better data are needed for the "seed" (primary) electrons from beam losses. Electron-proton (e-p) instability modeling is ongoing but was not discussed.

Detailed beam-loss studies (with a stripper foil inserted in the beam and with local closed orbit bumps) were carried out to quantify the sources of seed electrons and their effects on the prompt and swept electrons—different components of the EC exhibit very different properties and dependencies on machine and surface conditions. The prompt signal was found to be linear over a very wide range of relative beam losses or vacuum pressure changes (turning off pumps locally). These results can be applied to other machines where beam losses are important—in particular, heavy-ion rings and linacs.

Suppression of the EC was also studied, with somewhat mixed results. TiN coatings suppressed the prompt electrons by factors of 40 and 100 in two locations, respectively, but not at all in a third location (these data were obtained over a three-year period). The application of a ~20-G solenoidal magnetic field suppressed the prompt electrons in a 0.5-m section by a factor of 50. Beam conditioning over time reduced the prompt signals and improved the instability threshold curves.

More recent studies were reported, and some unresolved issues remain under study. An electron "burst" phenomenon was observed. Also, far below the e-p instability threshold, an interesting beam response to a weak kick has been observed that appears to be due to a combination of the ring impedance and the EC. Finally, a slow recovery of the electron cloud over about five turns (~2 μs) was observed after the gap was cleared with the sweeper. There is evidence that this may be related to multipacting and electron trapping in the quadrupole fields; a steady source of seed electrons is produced at the quadrupoles by grazing proton losses. Future plans call for installing a specially designed RFA in a quadrupole to study this effect.

J-PARC, Japan Proton Accelerator Research Complex (3-GeV RCS and 50-GeV MR)

The bunch structure and population in the J-PARC ring designs are similar to the PSR, motivating the study of possible electron cloud effects. T. Toyama reported on simulations of EC buildup and EC instabilities (ECI) for bunched and coasting beams. The coasting beam is stable, but the bunched beam parameters are close to instability thresholds, assuming δ_0 = 0.5 and maximum value δ_{max} =

2.1 for SS. A TiN coating is considered essential, especially during the commissioning process with unconditioned chambers. Simulations further show that the EC build-up is not in the saturation regime; this implies that reducing the seed electrons can directly reduce the cloud density. T. Toyama and his colleagues analyzed the electron yield (seed electrons) from many controlled and uncontrolled sources of beam loss (halo collimator, injection stripper foil, etc.), using proton-induced electron production rates quoted in the literature. It is assumed that solenoids will suppress these electrons from interacting with the beam. T. Toyama also reported on experimental studies in the KEK Proton Synchrotron (PS) that are being used to benchmark the simulations and help quantify beam losses; this is summarized below.

KEK PS (12-GeV PS MR)

An electron sweeper was installed in the Main Ring (MR), and studies were carried out for bunched and coasting beams. Build-up of the prompt electron signal is clearly seen when all nine bunches are injected. Very little build-up is observed with five or fewer bunches (the gap is greater than ~500 ns). When the sweeper is used to clear the gap, a slow recovery of the EC is observed (over ~1 μs), similar to that reported in the PSR. Analysis of the coasting beam swept data gives an electron decay constant of ~300 ms and a local neutralization factor of ~30%. These values appear to vary significantly from those obtained in the PSR; it would be interesting to analyze the differences. It was verified that reducing the MR beam intensity strongly reduced the electron cloud density. Finally, the electron production rate computed from the data was $\sim 3\times 10^{-9}$ e/m/p (electrons per meter per proton). It appears that a value of 4×10^{-6} e/m/p was derived from the literature. (This large discrepancy was not discussed; however, these results may be misinterpreted in this summary.)

HEAVY-ION RINGS AND LINACS

Heavy-ion rings and linacs have also been found in recent years to suffer from electron cloud effects, although the main concerns are rather different from the machines discussed so far.

RHIC

W. Fischer reported on recent comprehensive studies carried out at the Relativistic Heavy-Ion Collider (RHIC) at BNL. A fast pressure rise was observed in the warm chambers with Au^{79+}, d^{+}, and p that can cause gate valve closures at a threshold beam intensity. The pressure rise is consistent with EC-stimulated gas desorption; this suggests that the electron cloud is most critical insofar as it creates runaway pressure rise. The effect is confirmed at injection and is likely to also occur during the store. Extensive details of this phenomenon at RHIC and elsewhere can be found in the proceedings of a recent workshop [7].

The presence of the electron cloud has been confirmed in numerous ways: indirectly through the coherent tune shift along a bunch train (a technique first used at KEKB) and the vacuum pressure, and directly with dedicated RFA-type electron detectors. There is a clear correlation between the beam intensity, the measured electron cloud signal, and the vacuum pressure. Calculations carried out by M. Blaskiewicz using his CSEC code compare well with the measured data, using surface parameters $\delta_0 = 0.6$ and $\delta_{max} = 1.8$ that are consistent with the literature.

Additional studies were also carried out. The pressure rise at injection is very sensitive to the bunch spacing, suggesting a multipacting phenomenon. With stored beams, a pressure rise of more than a decade is also sometimes observed after a rebucketing process at the end of the energy ramp, during which the bunch length is reduced in half. There is a curious “switch-off” phenomenon sometimes observed minutes to hours after rebucketing at which point the vacuum pressure suddenly drops. These effects are insensitive to the beam energy and are not entirely reproducible, leading to speculation about the details of the physics of the beam-cloud-surface interactions; U. Iriso-Ariz and S. Peggs have proposed a possible first-order phase transition mechanism.

A. Drees reported additional experimental results on the effects of vacuum pressure evolution at two collision points, which are found to differ from each other. Unacceptable backgrounds are produced at one detector, while high trigger rates are produced at the other. The calculated accidental collision rate is consistent with beam-gas and can be used to benchmark different models for EC simulations.

With G. Rumolo, an important calculation result was found at collisions, during which the bunch spacing varies. It may be sufficient to suppress the EC at the ends of the Be pipe surrounding the collision point. The Be surface parameters were calibrated against both CERN data and detector background data.

Various countermeasures were studied. *In-situ* baking and NEG coating were highly effective in reducing the pressure rise in warm-section tests and will be implemented more widely in the future. Bunch patterns that minimize the pressure rise can be used. Solenoids and beam scrubbing appear to be effective, but immediate implementation of these techniques is not planned. Finally, ongoing studies of electron cloud effects measured in the cold chambers are also of great interest for the LHC.

Heavy-Ion Induction Linac for HIF

The heavy-ion induction linac at LLNL for heavy-ion fusion (HIF) can be considered an “extreme” beam compared with the machines considered thus far. A high line-charge density is combined with a large transverse fill fraction; a direct consequence is high beam (ion) loss on the walls at the quadrupoles, not unlike in the PSR. Beam losses result in ion-induced electron emission, ion scattering, and gas desorption. The latter is expected to cause the main source of EC: if the beam ionizes the desorbed gas, the liberated electrons become deeply trapped. Trapping of secondary electrons produced by beam head losses is also important, so control of the beam head is important. Trailing-edge multipacting is not an issue due to the long gap between pulses (> 0.2 s).

A. Molvik reported on the numerous experimental techniques developed to study electron cloud effects in the High-Current Experiment (HCX) linac, especially in the quadrupoles. Various gas-electron diagnostics, electron suppressors, and clearing electrodes were installed and mitigation techniques studied. The data analysis is combined with a close partnership with theory to derive electron emission and gas desorption rates, and an effort was made to remove diagnostic systematics.

A special Gas-Electron Source Diagnostic (GESD) measures calibrated electron and gas emission coefficients from grazing-incident K^+ ions. The scaling with ion energy was also measured and compared with an electron-sputtering model. The effects of baking, cleaning, and surface treatment—roughened (glass-bead blasted) and sawtooth surfaces as proposed at CERN—were evaluated. Ion backscattering, electron emission, and gas desorption were all significantly reduced by surface treatment, especially by the more effective but expensive sawtooth surface.

In the HCX, electron suppressor rings and clearing electrodes between the quadrupoles were found to be effective, improving the beam quality as observed on a scintillator. The electron cloud is believed to contribute to an effect whereby the beam splits in three (trifurcates) after it passes through a circular bore and slit. Quadrupole magnetic field errors also contribute. Study of the beam dynamics including electron trapping in the quadrupoles is ongoing, and futher experimental and theoretical studies are planned.

HIGH-ENERGY POSITRON/ELECTRON RINGS

e^+e^- *Colliders*

A. Novokhatski showed recent data from the PEPII B-factory at SLAC (comparative recent data from the KEKB B-factory were presented in the previous session). He described in detail the effect of the solenoidal fields on the electron cloud in the Low-Energy Ring (LER), which contains the positron beam, as inferred from the vacuum pressure readings. The ion gauge (or vacuum pump) magnet was at times removed, in which case the electron cloud wall-bombardment signal was acquired, as in an RFA. The solenoids can be seen to act like an "electron cloud" vacuum cleaner or "multipacting" cleaner, whereby the "pressure" reading (electron cloud signal) diminished sharply with the optimum solenoid field, bunch current, and beam store time. Up to about 1.3 mA bunch current, a weak solenoid field reduced the electron cloud. Simulations of positron bunch trains show that the solenoid field significantly reduces the average energy of the electrons colliding with the walls, which in turn influences the cloud density assuming an appropriate secondary emission yield coefficient curve $\delta(E)$, where E is the incident electron energy. The best agreement with the measured data was obtained when a $\delta(E)$ curve lying between as-received and conditioned SS (measured by R. Kirby) was used in the simulation.

A. Temnykh informally showed a few slides on new observations at the collider at CESR. The transverse bunch tune shifts show a variation with bunch spacing, with a larger vertical tune shift that may be a dipole field effect, or else related to the elliptical beam distribution. The electron cloud has an effect on the electron beam as well. A. Temnykh presented speculation on the effects of the leading electron or positron bunch and ionization of the residual gas, and the dynamics among later bunches, electron cloud electrons, and long-lived ions.

SUMMARY

Efforts at several proton, positron, electron (colliders), and ion rings and linacs continue to characterize and fine-tune our understanding of electron cloud effects and the generation and suppression of electron clouds. An incomplete outline of the topics presented and related machines follows:

- EC suppression
  - Scrubbing (SPS, RHIC)
  - Solenoid (PEPII, KEKB, KEK-PS, RHIC, PSR)
  - TiN, NEG (PEPII, PSR, RHIC, SPS, others)
  - EC Collectors (HCX, KEK-PS)
- EC vs. pressure (RHIC, SPS, KEKB, PEPII)
- Bunch length effect (SPS, RHIC)
- Memory effect and EC lifetime (PSR, KEKB, KEK-PS, SPS)
- New EC diagnostics
  - RFA in quads (SPS, PSR (planned))
  - EC sweeper (PSR, KEK-PS)
  - HCX GESD: electron and gas emission rates
  - Microwave TE (more work needed)

Significant progress has been made in identifying and quantifying those surface parameters most critical in the accurate prediction of electron cloud effects. A strong focus of experimental efforts is in benchmarking analytical and numerical modeling with measured data, and some consistency is emerging, although work remains to be done. For further background, the reader may wish to refer to review talks given at recent U.S. and European Particle Accelerator Conferences and other references [5,8-15].

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